nism. If the appropriate individual single-neutron-transfer cross sections can be determined experimentally, as in the present work, one can have greater confidence that the sequential amplitudes have been taken into account properly.

This work was done with support from the U. S. Energy and Research Development Administration. One of us (W.R.P.) wishes to thank the J. H. Williams Laboratory for its hospitality during his stay at the University of Minnesota.

[(a)]Present address: Daresbury Laboratory, Warrington WA4 4AD, United Kingdom.

[(b)]Present address: University of Manchester, Manchester M13 9PL, United Kingdom.

[1]B. F. Bayman, Phys. Rev. Lett. 32, 71 (1974).

[2]T. Takemasa, Phys. Lett. 55B, 28 (1975).

[3]L. A. Charlton, Nucl. Phys. A241, 144 (1975).

[4]A. J. Baltz and S. Kahana, Phys. Rev. Lett. 29, 1267 (1972).

[5]B. F. Bayman, Nucl. Phys. A168, 1 (1971).

[6]V. S. Mathur and J. R. Rook, Nucl. Phys. A91, 305 (1967).

[7]R. J. Ascuitto and N. K. Glendenning, Phys. Lett. 45B, 85 (1973).

[8]K. Yagi, D. L. Hendrie, L. Krass, C. F. Maguire, J. Mahoney, D. K. Scott, Y. Terrien, T. Udagawa, K. S. Low, and T. Tamura, Phys. Rev. Lett. 34, 95 (1975).

[9]U. Götz, M. Ichimura, R. A. Broglia, and A. Winther, Phys. Rep. 16C, 115 (1975).

[10]D. H. Feng, T. Tamura, T. Udagawa, J. Lynch, and K. S. Low, Phys. Rev. C 14, 1484 (1976).

[11]D. H. Feng, T. Udagawa, and T. Tamura, Nucl. Phys. A274, 262 (1976).

[12]B. F. Bayman, unpublished calculations.

[13]M. A. Franey, J. S. Lilley, and W. R. Phillips, to be published.

[14]W. W. True, Phys. Rev. 168, 1388 (1968).

[15]T. Engeland and P. J. Ellis, Nucl. Phys. A144, 161 (1970).

[16]R. M. Drisko and F. Rybicki, Phys. Rev. Lett. 16, 275 (1966).

[17]R. A. Broglia and A. Winther, Phys. Rep. 4C, 153 (1972).

[18]Coupled-channels program of P. D. Kunz (unpublished) and modified for heavy ions by L. D. Rickertsen.

[19]W. R. Coker, T. Udagawa, and H. H. Wolter, Phys. Rev. C 7, 1154 (1973).

[20]V. Gillet, A. M. Green, and E. A. Sanderson, Nucl. Phys. A88, 321 (1966).

Fine Structure in the Fusion Cross Section for $^{16}O + ^{12}C$

P. Taras, G. R. Rao,[(a)] and G. Azuelos[(b)]

Laboratoire de Physique Nucléaire, Université de Montréal, Montréal, Québec H3C 3J7, Canada

(Received 19 June 1978)

γ-ray excitation functions have been measured for several residual nuclei in the $^{12}C + ^{16}O$ system, from $E_{c.m.} = 12.2$ to 15.0 MeV in steps of ~ 27 keV. In addition to three known resonances, a fine correlated structure is found superimposed over a broad resonance, as suggested by the mechanism of a fragmented shape resonance. The data may also be interpreted to indicate that the system decays via two different paths.

During the past two or three years several resonances of the same spin and similar energy have been reported[1,2] in the $^{12}C + ^{12}C$ and $^{12}C + ^{16}O$ systems. This resonance clustering has led Feshbach[2] and Fletcher *et al.*[3] to suggest that we are witnessing a fragmentation of a wide shape resonance via a weak coupling of the incoming partial wave to the excited states of the interacting ions. However, many of the resonances have not been proven[1] to be nonstatistical in nature.

In this Letter, we report on the γ-ray yield measurement for several residual nuclei in the $^{12}C + ^{16}O$ system, from $E_{c.m.} = 12.2$ to 15.0 MeV. In addition to three known[4-6] resonances at 12.8, 13.7, and 14.8 MeV c.m., we find for the first time a fine structure in the fusion cross section. This fine structure, about 70 keV wide, superimposed over a gross structure, approximately 2 MeV wide, presents for the first time a direct visualization of a fragmented wide shape resonance. Furthermore, resonances of different widths are also observed, suggesting that the system decays via two different paths.

The experiment was performed using ^{16}O beams from the Université de Montréal *EN* tandem accelerator. The targets of natural C, having an effective thickness of about 12 $\mu g/cm^2$, were evaporated onto thick Ta backings. They were surrounded by a liquid-nitrogen-cooled shield which effectively limited the carbon buildup, if any, to less than 1% over a period of 96 hours. The mean beam energy loss in the target was of the order of 44 keV at 32-MeV incident beam energy. Data were taken in steps of 62.5 keV from 28.5 to 33.0 MeV, and in steps of 125 keV from 33.0 to 35.0 MeV, all energies being expressed in the laboratory system. The γ-ray energy spectra up to $E_\gamma = 2.5$ MeV were measured with a Ge(Li) detector, having an efficiency of 21%, and located at 90° to the incident beam and 9 cm from the target.

The spectra were dominated by photopeaks attributed to the following exit channels: ^{24}Mg $+\alpha(E_\gamma = 1369$ keV), ^{23}Na$+\alpha p$(440 keV), ^{20}Ne $+2\alpha$(1634 keV), ^{26}Mg$+2p$(1809 keV), ^{26}Al$+pn$(417 keV), and the Coulomb excitation of the tantalum backing. Although the ^{27}Al$+p$ channel accounts[7] for ~20% of the fusion cross section near $E_{\rm c.m.} = 12$ MeV, the particular nature of the branching among the low-lying states does not result in significant yields of the 844- or 1014-keV γ rays. However, if the intensities of all the weak ground-state transitions are summed, an appreciable yield results for this channel, but with an error too large to yield a meaningful excitation function. In addition, charged-particle spectra[5] show that a large number of levels is indeed populated in this range in ^{27}Al.

Excitation functions are displayed in Fig. 1. They have been corrected for the relative efficiency of the Ge(Li) detector using a ^{154}Eu source. Typical uncertainties in the relative yields vary from (2–4)%. The top curve in Fig. 1 labeled "total" represents the summation of all the γ-ray yield curves shown and is expected[7] to represent nearly 80% of the actual fusion cross section in this energy range. The γ rays can be considered to be emitted by the recoiling fragments after particle evaporation from the fused system.

The peak-to-valley ratios, of the order of 10%, observed in the fusion cross section are consistent with those obtained[7,8] in some other fusion-cross-section measurements, but with much coarser energy steps (typically ~500 keV lab), and in different energy ranges.

It is highly unlikely that the observed structures correspond to statistical fluctuations. The effective integration over all angles of particle emission and most individual transitions in the residual nuclei, inherent in a γ-ray yield measurement, leads to large damping effects. For example, we obtain a cross-correlation coefficient of 0.5 between the α and αp channels, computed over the whole energy range, while a zero value is expected if these two channels are statistically independent. A complete statistical analysis will appear in Ref. 5.

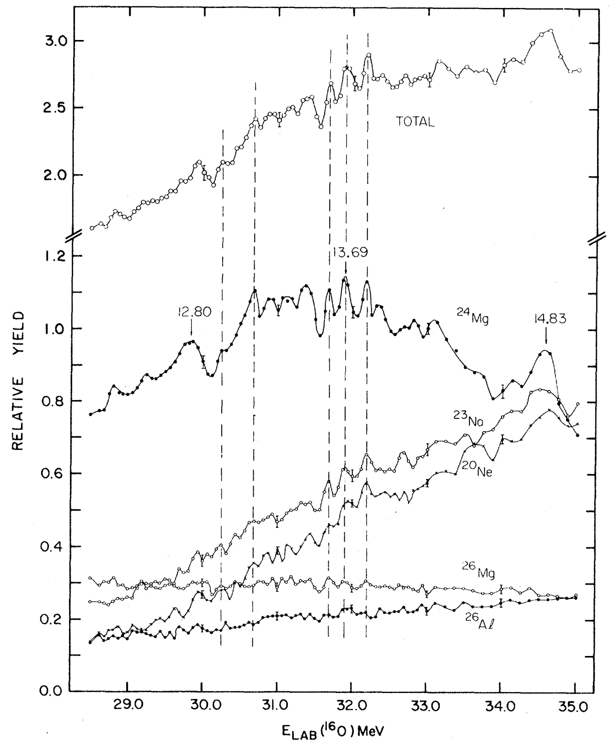

FIG. 1. γ-ray excitation functions for several residual nuclei in the ^{12}C$+^{16}$O system, corrected for the relative efficiency of the Ge(Li) detector. The top curve labeled "total" is a summation of all the excitation functions and is expected to represent ~80% of the fusion cross section.

Calculations performed with the code HAUSER by Christensen, Switkowski, and Dayras[7] indicate, as explained in detail in Ref. 5, that over our energy range, sequential decay into ^{23}Na and ^{20}Ne following the ^{24}Mg$+\alpha$ exit channel must be, on the average, less than 10%. In addition, a sequential decay cannot possibly be a general explanation of the observed effects. In the limited energy range studied, one cannot expect to have sometines sequential decay and at other times simultaneous three-body breakup; i.e., all the peaks in the α channel should also be found in the αp and 2α channels, if sequential decay is the predominant mechanism. This is not the case. Furthermore, correlated effects are also observed in the $2p$ channel which cannot possibly arise from sequential decay following the emission of α particles.

Also, the observed effects cannot be due to a special selectivity of high-spin states since calculations by Greenwood *et al.*[9] show that for this reaction, in this energy range, the number of open channels is larger than 10^4 for $J = (5-9)\hbar$.

Furthermore, our statistical calculations[5] give a value of $N_{eff} \sim 500$ from the α exit channel alone.

Thus, it can be surmised that, in addition to three known[4-6] resonances at 12.8, 13.7, and 14.8 MeV c.m., a fine structure, about 70 keV wide, is found in the total fusion cross section. This fine structure, partly correlated, reveals itself most clearly in the α exit channel where it is superimposed over a gross structure, approximately 2 MeV wide. There are two new strongly correlated resonances at 13.6 and 13.8 MeV, and more weakly correlated structures at 13.0, 13.2, 13.3, 13.5, and 14.2 MeV.

The fine structure could be related to the fragmentation of wide shape resonances evoked by Feshbach[2] and Fletcher *et al.*[3] Using the semiclassical expression for the grazing orbit with a radius parameter r_0 of 1.50 fm, we find an $L=9$ partial wave at 13.73 MeV (c.m.), close to the centroid of the gross structure. In addition, the 13.7-MeV resonance has previously[6] been assigned $J^\pi = 9^-$. However, spins and reduced partial widths of the narrow resonances will have to be measured before it can be stated that the fine structure is definitely related to the underlying gross structure, as suggested by the fragmentation picture.

Another interesting aspect of the data is revealed by the different widths of the 12.8- and 14.8-MeV resonances ($\Gamma_{c.m.} \sim 150$ keV) as compared with those of the fine structure ($\Gamma_{c.m.} \sim 70$ keV). These results indicate that the former resonances decay directly from their doorway-state structure (i.e., a dinuclear molecular or α-cluster configuration) while the narrower resonances would arise from the doorway states decaying entirely through the compound nucleus, making it more probable that the structure will be seen in all the exit channels, as appears to be the case.

The authors would like to thank Dr. R. A. Dayras for useful discussions on the statistical analysis of γ-ray excitation functions. This research was partially supported by the National Research Council of Canada.

[a]Present address: Nuclear Physics Laboratory, University of Pittsburgh, Pittsburgh, Penn. 15260.

[b]Present address: Department of Physics and Astronomy, Tel-Aviv University, Ramat-Aviv, Tel-Aviv, Israel.

[1]D. A. Bromley, in *Nuclear Molecular Phenomena*, edited by N. Cindro (North-Holland, Amsterdam, 1978), p. 3.

[2]H. Feshbach, J. Phys. (Paris) Colloq. 37, C5-177 (1976), and in *Proceedings of the Europhysical Society International Conference on Physics of Medium Light Nuclei, Florence, Italy, June, 1977*, edited by P. Blasi and R. A. Ricci (Editori Compositori, Bologna, 1978), p. 394.

[3]N. R. Fletcher, J. D. Fox, G. J. KeKelis, G. R. Morgan, and G. A. Norton, Phys. Rev. C 13, 1173 (1976).

[4]P. Taras, G. R. Rao, N. Schulz, J. P. Vivien, B. Haas, J. C. Merdinger, and S. Landsberger, Phys. Rev. C 15, 834 (1977).

[5]G. R. Rao *et al.*, to be published.

[6]D. Brandford, J. O. Newton, J. M. Robinson, and B. N. Nagorcka, J. Phys. A 7, 1193 (1974); R. E. Malmin, J. W. Harris, and P. Paul, Phys. Rev. C 18, 163 (1978).

[7]P. R. Christensen, Z. E. Switkowski, and R. A. Dayras, Nucl. Phys. A280, 189 (1977).

[8]J. J. Kolata, R. M. Freeman, F. Haas, B. Heusch, and A. Gallmann, Phys. Lett. 65B, 333 (1976).

[9]L. R. Greenwood, K. Katori, R. E. Malmin, T. H. Braid, J. C. Stolzfus, and R. H. Siemssen, Phys. Rev. C 6, 2112 (1972).